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6. AUTHOR(S)
Osamu ISHIHARA

2301/ES
61102F

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Texas Tech University
Department of Electrical Engineering
Lubbock, TX 79409-3102

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NE
Dr. Robert J. Barker
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-0001

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13. ABSTRACT (Maximum 200 words)

This final technical report describes the research results of theoretical and computational analyses of wave-particle interaction in plasma turbulence. (1) We developed the extended resonance broadening theory of plasma turbulence in which anomalous particle diffusion in strong plasma turbulence was revealed. (2) As a new approach to plasma turbulence theory, wave-particle interaction was studied in a framework of quantum electrodynamics which allows the inclusion of self-fields created by energetic plasma electrons. (3) A MAGIC simulation code was used to study plasma turbulence and its interaction with photons. (4) A MAGIC code was also used to study plasma interaction with microwaves in a Vircator high power microwave device. (5) Collective effects in plasmas were studied in the presence of dusts in a plasma

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on

Study of Advanced Applications of Wave-Particle Interaction
(Grant No. F49620-93-1-0137)

for the period of
February 1, 1993 to January 31, 1996

Submitted to
Air Force Office of Scientific Research

by

Osamu Ishihara
Professor
Department of Electrical Engineering
Texas Tech University
Lubbock, TX 79409-3102

for
Dr. Robert Barker
Directorate of Physics and Electronics
Air Force Office of Scientific Research/NE
110 Duncan Ave, Suite B115
Bolling Air Force Base
Washington, D.C. 20332-0001

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Principal Investigator: Osamu Ishihara
Phone (806) 742-3463
Fax (806) 742-1245
E-mail oishihara@coe2.coe.ttu.edu
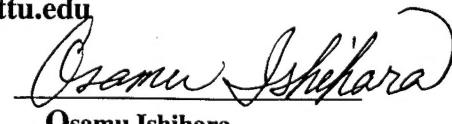
Osamu Ishihara
Principal Investigator

I. SUMMARY

This is a final technical report of the project "Study of Advanced Application of Wave-Particle Interaction." (AFOSR Grant No. F49620-93-1-0137). Theoretical and computational analysis of wave-particle interaction in plasma turbulence has been carried out at Texas Tech University. During the period of February 1, 1993 to January 31, 1996, 8 journal publications, three publications in special topic books, eleven conference abstracts, and one dissertation were produced.

II. RESEARCH OBJECTIVES

Objectives of this program were to explore novel applications of wave-particle interaction associated with plasma turbulence. To achieve this goal, theoretical and computational approaches were taken. Theoretical approaches include both classical and quantum approaches, while the computational approach depends on the test particle numerical experiment and MAGIC (Magnetic Insulation Code) particle simulation code developed by the Mission Research Corporation under the sponsorship of AFOSR.

III. RESEARCH

Extended Resonance Broadening Theory of Plasma Turbulence ---Theoretical and computational study of moderately strong plasma turbulence, developed as an extended resonance broadening theory, completed with a publication and was reviewed in a book *Statistical Description of Transport in Plasma, Astro and Nuclear Physics.*

Quantum Electrodynamical Approach to Plasma Turbulence --- Theoretical work on wave-particle interaction in plasma turbulence was studied in a framework of quantum electrodynamics. The theory treats the effect of self-fields created by energetic plasma electrons on the wave-particle interaction. The result is published as an article in a book *Transport, Chaos and Plasma Physics.*

MAGIC Simulation of Plasma Turbulence --- A two and a half dimensional particle simulation code was used to simulate the plasma turbulence. By injecting nonrelativistic and relativistic electron beams in a plasma, electrostatic and electromagnetic instabilities are studied. After the plasma turbulence is established, photons are injected in a plasma. Due to the coupling between the photon and plasma turbulence, higher frequency photons are observed. John Masten wrote his dissertation on this subject.

MAGIC Simulation of VIRCATOR --- Although VIRCATOR simulation was not in our original proposal, discussion between the principal investigator and the Himeji experimental group in Japan prompted us to simulate their experimental finding on

their VIRCATOR. The MAGIC is capable to simulate Himeji experiment in which bipolar flow in the diode region affects the condition of generation of the high power microwaves. A graduate student, Doug Young, runs the simulation and the strong pinching in the Vircator diode is observed in the presence of anode plasma. Mr. Young is preparing his master thesis on this subject.

Plasma Crystal Formation - - - Theoretical investigation revealed that charged dust grains in a plasma sheath region can attract each other when they were trapped in the potential minima associated with the trailing wake potential behind the dust particle in the presence of ion acoustic oscillations. The attraction between highly charged dust particles may explain the observed crystal formation in a dusty plasma. The result is published in the Physics of Plasmas.

IV. LISTINGS OF PUBLICATIONS

Publications, together with the abstracts, of the research results obtained under the contract AFOSR Grant No. F49620-93-1-0137 are listed here.

1. Non-Markovian Diffusion in Plasma Turbulence, H. Xia, O. Ishihara and A. Hirose, Physics of Fluids B **5**, 2892-2904 (1993).

Motion of charged particles in electrostatic plasma turbulence is studied analytically and numerically. Analytical study is based on a stochastic differential equation, the generalized Langevin equation, which is derived by the projection operator method with the assumption that the random fluctuation field is a Gaussian and wide sense stationary process. The equation describes the particle velocity as a stochastic process driven by field fluctuations, and is applied to evaluate the velocity diffusion coefficient. The non-Markovian velocity diffusivity is characterized by the retarded turbulent collision term which contributes to the memory effect of the wave–particle interaction. Test-particle numerical experiments are carried out by following trajectories of charged particles in Langmuir turbulence. The observed diffusion coefficient in a relatively strong turbulence deviates from predicted values of the quasilinear and the extended resonance broadening theories. The present non-Markovian formulation explains well such a departure of the diffusion rate.

2. Long-Time Diffusion in Plasma Turbulence with Broad Uniform Spectrum, O. Ishihara, H. Xia, and S. Watanabe, Physics of Fluids B **5**, 2786-2792 (1993).

The long-time behavior of charged particles in plasma turbulence with uniform broad wave spectrum is studied numerically. The diffusivity of the particle velocity distribution is characterized by the quasilinear nature for extended time, while a transient diffusion precedes with the enhanced nonquasilinear diffusion rate when resonance overlapping is relatively weak. The observed long-time quasilinear diffusion coefficient eventually decreases due to the finiteness of the resonance region. The transient-type diffusion is revealed only by the higher-order numerical calculation.

3. "Quantum Electrodynamical Approach to Plasma Turbulence," O. Ishihara *Transport, Chaos and Plasma Physics*, ed. by S. Benkadda, F. Doveil and Y.Elskens (World Scientific, Singapore, 1993) pp. 389-392.

Wave-particle interaction in plasma turbulence is studied from the viewpoint of quantum electrodynamics. The waves in a plasma turbulence are considered as a collection of quasiparticles. These quasiparticles interact with particles of the plasma and the interactions are described in terms of a Dirac interaction Hamiltonian. A modified Fermi golden rule is used to describe the rate of change of the particle distribution function. A radiative, collective, resonant and nonresonant effects are discussed.

4. "Plasma Turbulent Bremsstrahlung," O. Ishihara and A. Hirose, Physical Review Letters **72**, 4090 (1994).

Plasma turbulent bremsstrahlung is a radiation of high frequency plasma mode produced by the scattered electrons due to the effective turbulent collisions associated with low frequency fluctuations. It is found that the spontaneous emission term in the quasilinear effect is responsible for the mechanism. The Langmuir mode becomes unstable when electrons resonate with low frequency modes in the presence of ion acoustic turbulence resulting in frequency upconversion.

5. "Resonance Broadening Theory Revisited," A. Hirose and O. Ishihara, *Statistical Description of Transport in Plasma, Astro and Nuclear Physics*, (Nova Science, New York, 1994), p.131.

Abstract. It is shown that the velocity variance in one dimensional electrostatic turbulence is not pure Brownian but subdiffusive $\langle v^2 \rangle \propto t^\alpha, \alpha = 1/2 - 2/3$, with a corresponding diffusivity decreasing with time as $D \propto 1/t^{\alpha-1}$. The fractional Brownian motion associated with the diffusion process is attributed to non-Markovian statistics of particle trajectories.

6. "Frequency Upconversion in Plasma Turbulence, O. Ishihara, *Current Topics in the Physics of Fluids,* ed. by the Council of Scientific Information, (Trivandrum, India, 1995).

Frequency upconversion in electrostatic plasma turbulence is studied theoretically. A test Langmuir wave launched into the ion acoustic turbulence is found to grow with time, resulting in the upconversion of frequency from the range of below ω_{pi} (ion plasma frequency) to the range of ω_{pe} (electron plasma frequency) in the turbulent frequency spectrum. The Langmuir wave emission results from the scattering of electrons by plasma turbulence in which electrons resonate with low frequency ion acoustic modes. Turbulent collisions produce an emission of electrostatic waves, similar to the bremsstrahlung effect on electrons, and the mechanism may be called plasma turbulent bremsstrahlung. The analysis is based on the interaction of wave-particle and wave-wave coupling. Correlation of fluctuations in electron distribution in the presence of turbulent fields plays an essential role in the emission process.

7. On Plasma Crystal Formation, S.V. Vladimirov and O. Ishihara, Physics of Plasmas **3**, 444-446 (1996).

It is shown that charged dust grains in a sheath region with plasma ion flow can attract each other in the wake potential cone of an upstream dust particulate. Because of the periodic nature of the potential, periodic structures of the dust grains can be formed in a base plane of the cone. © *1996 American Institute of Physics.* [S1070-664X(96)04902-0]

8. Spontaneous Emission Effects in Nonlinear Interactions of Nonresonant Waves with Resonant Plasma Fluctuations, S.V. Vladimirov and O. Ishihara, Physics of Plasmas **3**, 673-681(1996).

Spontaneous emission effects on propagation of nonresonant waves in plasmas in the presence of resonant fluctuations are studied. It is demonstrated that in closed plasma systems the number of nonresonant quanta is conserved as an adiabatic invariant. The conservation is due to the vanishing polarizational contribution that resulted from the symmetry of the system as well as to the balance of the direct nonlinear coupling and reverse absorption by particle collisions. Energy of the nonresonant waves as well as their amplitudes may vary with time even when the resonant field fluctuations are at the thermal level. © *1996 American Institute of Physics.* [S1070-664X(96)02402-5]

V. LISTINGS OF CONFERENCE PRESENTATIONS

Conference presentations of the research results obtained under the contract AFOSR Grant No. F49620-93-1-0137 are listed here.

1. Effects of Bipolar Flow on Microwave Emission in a Vircator, D. Young, O. Ishihara, and M. Yatsuzuka, Bull. Am. Phys. Soc. **39**, 1747 (1994).

2. Electromagnetic Wave Interaction with Beam-Plasma Induced Turbulence, J. Masten and O. Ishihara, Bull. Am. Phys. Soc. **39**, 1659 (1994).

3. Magnetic Field Effect on Plasma Turbulent Bremsstrahlung, O. Ishihara, Bull. Am. Phys. Soc. **39**, 1656 (1994).

4. Magic Simulation of Nonrelativistic and Relativistic Beam-Plasma Instability, J. Masten and O. Ishihara, IEEE Int. Conf. Plasma Sci. (June 6-8, 1994, Santa Fe, NM).

5. A MAGIC Simulation Study of the Effects of Bipolar Flow on Microwave Emission in a Vircator, D. Young and O. Ishihara, IEEE Int. Conf. Plasma Sci. (June 6-8, 1994, Santa Fe, NM).

6. A PIC Simulation Study of Electron Beam Pinching and Microwave Emission in a Vircator, D. Young, O. Ishihara, and M. Yatsuzuka, Bull. Am. Phys. Soc. **40**, (1995).

7. Turbulent Scattering in Dusty Plasmas," O. Ishihara and S.V. Vladimirov, Bull. Am. Phys. Soc. **40**, (1995).

8. Effects of Electron Beam Pinching on Microwave Emission in a Vircator, D. Young, O. Ishihara, and M. Yatsuzuka, IEEE Int. Conf. on Plasma Sci. (June 5-8, 1995, Madison, WI).

9. Photon Interaction with Beam-Plasma Induced Electromagnetic Turbulence, J. Masten and O. Ishihara, IEEE Int. Conf. on Plasma Sci. (June 5-8, 1995, Madison, WI).

10. Temporal Evolution of Anode and Cathode Plasmas in a Vircator Diode, M. Yatsuzuka, M. Nakayama, Y. Hashimoto, K. Azuma, S. Nobuhara, and O. Ishihara, IEEE Int. Conf. on Plasma Sci. (June 5-8, 1995, Madison, WI).

11. Relativistic Beam-Plasma Instability and Its Interaction with Electromagnetic Wave, J. Masten and O. Ishihara, APS Texas Section Fall Meeting, (October 27-28, 1995, Lubbock, TX), Bull. Am. Phys. Soc. (1995).

12. On the Wake Potential of Dust Particles in a Plasma with Ion Flow, O. Ishihara and S.V.Vladimirov, IEEE Int. Conf. on Plasma Sci. (June 3-5, 1996, Boston, MA).

VI. DISSERTATION

John Masten completed his dissertation (December, 1995) under the support of AFOSR. The title of the dissertation is :

Relativistic Electron Beam-Plasma Instability and Interaction with Electromagnetic Wave

ABSTRACT

A plasma particle simulation was undertaken to study the growth rate of the relativistic beam-plasma electromagnetic instability. The linear dispersion relation for the relativistic beam-plasma electromagnetic instability is derived and solved numerically for the growth rate of the electromagnetic field. The linear growth rate is numerically tabulated as a function of beam velocity and wavenumber. The results are compared with plasma particle simulations conducted using MAGIC, a particle in cell code developed by Mission Research Corporation under the auspices of the Air Force Office of Scientific Research. The resulting growth rates, as a function of beam velocity and wavenumber, from the particle simulation agree with the linear theory. The saturation of the beam-plasma instability agrees with the quasi-linear theory. Electromagnetic turbulence develops from the relativistic beam-plasma instability. The interaction of the electromagnetic turbulence with an incident electromagnetic wave, at $\omega = \omega_p$ where ω_p is the plasma frequency, is studied by the use of the Fourier spectrum. A scattered wave spectrum is observed at $\omega = 2\omega_p$.

VII. STAFFING

Faculty investigator

Professor Osamu Ishihara of Department of Electrical Engineering and Physics at Texas Tech University is a principal investigator. Dr. Ishihara coordinates the overall project.

Graduate Students

Mr. John Masten, a native of Texas, is a doctoral student of the electrical engineering and is involved in the computational work on plasma turbulence. Mr. Masten is in the program "Augmentation Awards for Science and Engineering Research Training" (Department of Defense) since July, 1992. He has completed his PhD in December, 1995.

Mr. Douglas Young, a native of New Mexico, is a master student of the physics. Mr. Young is finishing his master thesis on Vircator in May, 1996 and continues his doctoral work.

Accountant:

Financial record is kept by Ms. Sandra Branch of the department of electrical engineering.